Wide Bandgap Power Electronics for Inertial Confinement Fusion

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Abstract

Inertial confinement fusion requires a wide variety of high-performance power electronics for operation. Commercial power plants will require devices with high reliability, that are fault-tolerant and easy to swap out when they malfunction, ideally without stopping the power reactor. This paper discusses power electronics developed under the ARPA-E GAMOW program for high-performance, high-power-density power electronics for fusion reactors.

Keywords: fusion, laser, inertial confinement fusion, power electronics, nuclear fusion

1. ARPA-E GAMOW

For more than 60 years, fusion research and development has focused on attaining the required fuel density, temperature, and energy confinement time required for a viable fusion energy system. To date, relatively modest investments have been made in the enabling technologies and advanced materials needed to sustain a commercially attractive fusion energy system. However, further innovations and advances are required to establish fusion energy's technical and commercial viability. The GAMOW program supports projects pursuing innovative R&D in fusion-energy subsystems and cross-cutting areas to enable commercially attractive fusion energy within the next several decades [1]. This paper discusses power electronics enabled by wide bandgap power transistors which are being developed under the ARPA-E GAMOW program, and their potential benefits for inertial confinement fusion reactors.

2. Wide Bandgap Power Transistors

2.1 Wide Band Gap Semiconductors

The energy required for electrons and holes to transition from the valence band to the conduction band is called a bandgap. Si (Silicon) has a bandgap of 1.12 eV (electron-Volts). A semiconductor with a large bandgap value is called a wide bandgap semiconductor. SiC (Silicon Carbide) and GaN (Gallium Nitride) are examples of wide bandgap semiconductors [2]. The wide bandgap allows a semiconductor to operate at higher voltages, which results in lower currents for a given operating power, and hence lower ohmic dissipation in the power distribution network.

SiC devices can be used up to 50 MHz, and possibly as high as 120 MHz. GaN can operate up to the GHz range and GaN-on-SIC can operate at even higher frequencies. A 50 MHz Class E amplifier utilizing SiC cascodes is shown in Figure 1 on the following page. The Class E is a switching amplifier with ideally 100%

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efficiency (given no phase errors), and can be used to generate electromagnetic waves [3].

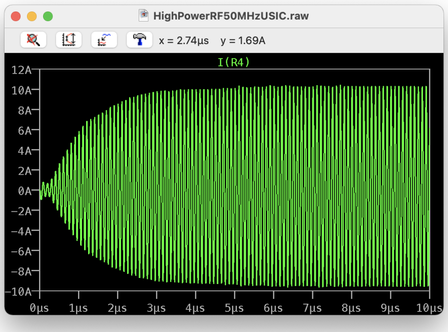

Figure 1: 50 MHz Class E amplifier using a Qorvo UF3C170400S3 cascode.

2.2 Qorvo SiC Cascodes

Qorvo's high-performance field-effect transistors (FETs) are based on a unique cascode configuration, where a high-performance SiC fast JFET is co-packaged with a cascode-optimized Si-MOSFET, enabling standard gate drive SiC device operation. The cascodes developed under ARPA-E GAMOW have 2 kV drain-to-source voltages.

UnitedSiC has developed the 2kV fabrication process through a series of process parameter Design of Experiments (DoEs), fabricated the prototype 2kV SiC JFETs based on its 4th Generation SiC Vertical Trench JFET platform, and performed wafer level die sort tests on the prototype devices. Based on wafer probe data, the new high-voltage Gen4 JFET design has successfully met its initial design targets with a median On-Resistance (for gate-source voltage VGS = 0 V) of 53 mOhms and drain-to-source breakdown voltage BVDSX(for VGS = -20 V) of 2,337V. To our knowledge, this represents a new record low specific on-resistance for a SiC FET with 2kV rating: 2.9mOhm-cm^2.

UnitedSiC's normally-Off cascode FETs are formed by co-packaging (either in side-by-side or die stack technology) low voltage Si MOSFETs along with high voltage SiC JFETs (as shown in Figure 2). For this project, since pulse voltages up to 1.5kV may be used in the Class E amplifiers, a 2kV Cascode FET packaged in a low-inductance SMT package (see Figure 3) was selected as the test vehicle. The design was targeted for a 60mOhm, 2kV normally-Off SiC FET by combining a 55mOhm/2kV SiC JFET in cascode with a 20V/3.5mOhm Si MOSFET. The anticipated UnitedSiC product would be designated as UF4SC20060B7S.

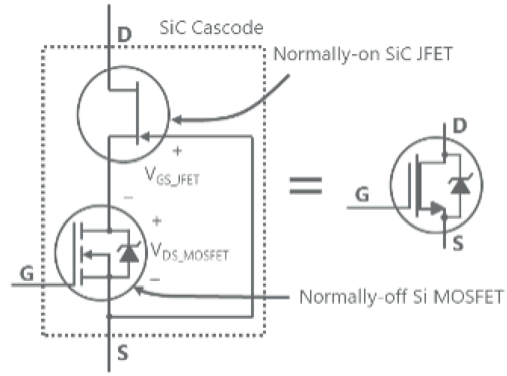

Figure 2: Schematic of UnitedSiC Normally-Off Cascode FET and configuration with Normally-On SiC vertical trench JFET.

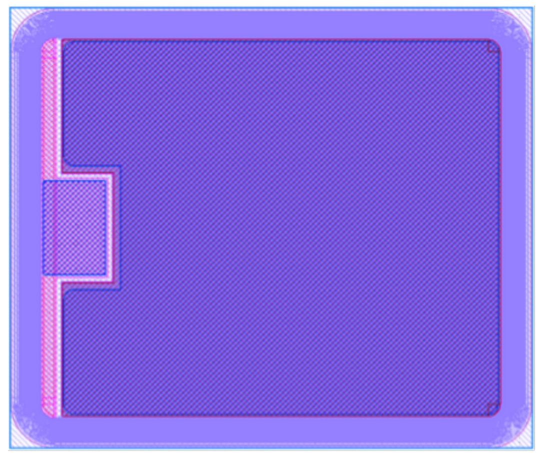

Figure 3: 2kV/55mOhm SIC JFET die (left) 2.7mm $\times$ 3.16mm including 80μm scribe and bonding diagram of 2kV/60mOhm Normally-Off cascode FET in D2Pak7L surface mount discrete (UF4SC200060B7S).

3. Modular Power Electronics

3.1 Board Concept

The electrical boards under development will use high-voltage (2 kV+) wide bandgap SiC cascodes produced by Qorvo. Up to 20 of these boards can be combined in a single chassis. The boards will include a novel plug-and-play interface which would allow a board to be removed from the chassis without turning off the system. There will also be active monitoring for fault detection and proactive maintenance, in addition to integrated thermal control. The chassis is designed to connect to a common thermal control system and will have radiation protection and electromagnetic interference (EMI) filtering to allow the boards to be placed near a fusion reactor.

3.2 Thermal Management

NREL is developing several high-performance thermal management systems for power fusion electrical boards to enable reliable and power-dense components. Extensive thermal modeling is being conducted using the Qorvo cascode semiconductor devices to predict thermal resistance under various operating conditions. Finite element analysis (FEA) is used to evaluate the effect of different substrate materials, different convective cooling strategies, and to evaluate the effect of semiconductor device spacing. The FEA will also identify the target heat transfer coefficient value. Computational fluid dynamics (CFD) is then used to design the heat exchanger to achieve the target heat transfer coefficient value while minimizing pumping power requirements.

To boost the capacity of power conversion, it is necessary to integrate as many devices as possible into one package. To understand how the density of devices affects the temperature profiles and cooling requirements, NREL developed a thermal FEA model of 16 devices in a 4x4 array with varying spacing and thickness. With a uniform heat transfer coefficient of 15,000 W/m^{2}K and coolant temperature of 65°C, the maximum junction temperature of 16 devices was computed with different spacing and thickness.

Based on the FEA results, a spacing of 0.1 mm was selected and the 4x4 device array was then created for further optimization, as shown in Figure 5. The objective of the optimization was to identify boundary conditions that provide high temperature uniformity and limit the maximum junction temperature below a prescribed value. Model-predicted results indicate that an HTC of 30,000 W/m^{2}K yields about a 2°C temperature difference across the board in terms of the maximum junction temperature, while the highest junction temperature of all devices is about 175°C. Therefore, this HTC value of 30,000 W/m^{2}K will be used as a target in the cooling system design. Surface enhancements may be required to achieve this HTC value, such as pin-fins, microchannels, or porous media, and the performance of various enhancements will be compared using the CFD tool.

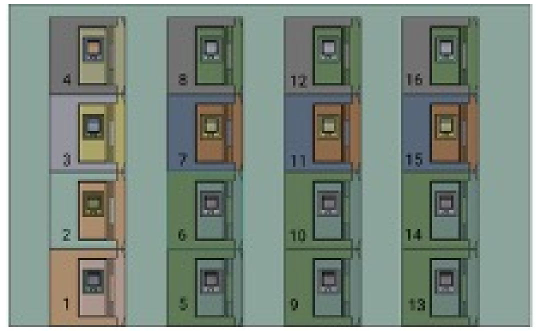

Figure 4: Schematic showing the 16 cascode devices in a 4 x 4 array. The spacing between devices is 0.1 mm and thickness is 1mm.

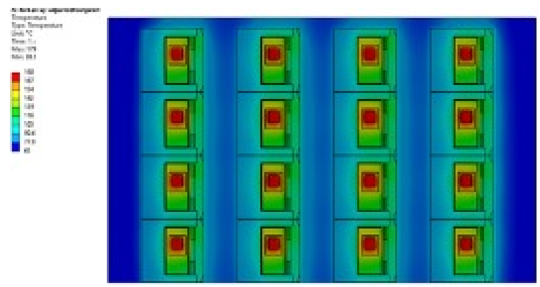

Figure 5: Temperature profile of devices after the multi-objective optimization.

3.3 Cooling Technologies

It is necessary to design cooling solutions that allow for quick removal or replacement of power boards without disruption to the overall system operation. With this in mind, the team is working on a concept that allows for ease of maintenance of the power boards, and provides high thermal performance. The cooling concept uses two-phase heat transfer cold plates that are integrated with the power boards to enable high heat transfer coefficients ($\geq$ 100,000 W/m^{2}K) near the devices. The power boards and cooling system assemblies mount onto cooling racks that ultimately dissipate the heat to facility cooling water systems. No-spill quick disconnects designed for liquid cooling of electronics will allow boards to be easily removed and reinserted into the rack. Water cooling systems should be readily available in all plasma fusion facilities for thermal management of equipment [4]. Drip-free connectors are used in a wide variety of rack mounted equipment that can be used for plug and play boards [5].

4. Inertial Confinement Fusion Power Electronics Needs

Inertial fusion is also a major branch of thermonuclear fusion. In an inertial fusion machine, laser pulses heat and compress a pellet of plasma fuel, typically a capsule of deuterium and tritium. Lasers shot at the fuel pellet heat the target's outer surface. When the heated layer explodes outward, a reaction force is produced, rapidly compressing the fuel inward into a core at high temperature and pressure.

This conception of having a driver directly heat the fuel pellet is called the “direct drive” approach. Although this method is simple and efficient, it is difficult to achieve uniform ignition and avoid instabilities due to asymmetry in practice. To address this issue, the concept of “indirect drive” was conceived. It employs the use of a hohlraum, a small cylinder in which the fuel capsule is suspended. Beams are shone into the lead or gold hohlraum, which emits x-rays that heat and pressurize the capsule. This improves the symmetry of implosion, but is less efficient than the direct drive method. Table 1 contains a list of the various types of inertial fusion systems.

A pertinent example with high power electronics needs is the National Ignition Facility (NIF) which uses an indirect drive system. The NIF power conditioning system achieves peak currents and power on the order of 10^8 A and 10^{12} W [6]. As NIF and other ICF systems advance in fusion power generation milestones, these pulsed systems will need to generate sufficient average power, thus requiring reliable energy at a high driver repetition rate [7]. Additional inertial confinement fusion systems including Magnetized Liner Inertial Fusion (MagLIF) [8] and General Fusion’s mechanical compression system [9], require 10^5 - 10^7 Amps of current in pulses ranging from nanoseconds to microseconds in length. These high-current, short-pulsed systems require adequate power electronics with high reliability. Our electrical boards are being developed for high-power, short-pulse applications, and with their plug-and-play architecture, advanced thermal management, and high-voltage tolerance (due to wide band gap semiconductor capabilities), these boards offer high reliability for the aforementioned fusion applications.

Table 1: Inertial fusion systems.

Device	Description
Indirect drive	Lasers heat a structure that then heat a small pellet of fuel, causing it to collapse inward to compress the fuel.
Direct drive	The lasers directly heat the fuel pellet.
Magneto-inertial fusion or Magnetized Liner Inertial Fusion	This combines a laser pulse with a magnetic pinch.
Heavy Ion Beams	Colliding beams are used to create fusion [10].
Magnetized Target Fusion	A preheated and magnetized plasma is compressed explosively [11].
Mechanical Compression	Uses pistons to compress a magnetized plasma [9]. A form of MTF.

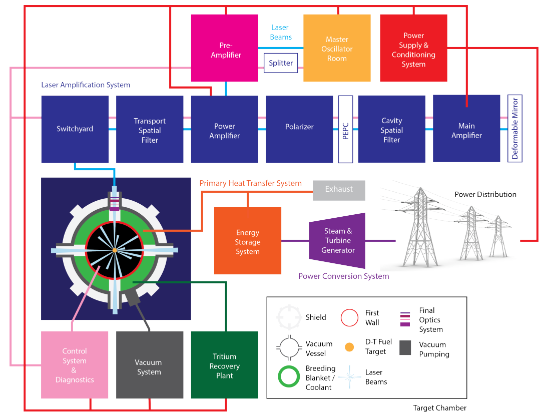

Figure 6: Conceptual diagram for a general inertial fusion power plant.

Table 2: Inertial confinement fusion device diagram components.

Component	Description
Power Supply and Conditioning System	Delivers voltage of proper levels and characteristics to other subsystem loads.
Master Oscillator Room	Where initial lower energy laser pulses are generated.
Splitter	Splits generated laser into multiple beams.
Pre-amplifier	Increases laser energy by a factor of 1 billion and shapes the beams precisely.
Deformable Mirror	Mirror that can have its surface deformed in order to achieve wavefront control and correct optical aberrations which improves the overall focus of the beams.
Main Amplifier	System of flash-lamps and laser glass that amplifies power of pulses that undergo multiple passes.
Cavity Spatial Filter	Condition beams after amplification in the main amplifier. Precisely concentrate the beams and eliminate scattered laser light to create high quality beams.
Plasma Electrode Pockels Cell (PEPC)	An optical switch that traps the beams until they make a sufficient amount of passes through the main amplifier.
Polarizer	Filter laser beams by only allowing certain waveforms to pass through.
Power Amplifier	Amplifies laser power in the first and final pass through the amplifier system.
Transport Spatial Filter	Condition beams after amplification in the power amplifier. Precisely concentrate the beams and eliminate scattered laser light to create high quality beams.
Switchyard	A system of transport mirrors that redirects the beams to the upper and lower hemispheres of the Target Chamber and configures them uniformly around the target fuel.
Shield	Separates fusion equipment inside the chamber from the environment.
Vacuum Vessel	Low-pressure environment within the chamber from which gases are removed to create a vacuum.
Breeding Blanket / Coolant	Acts as a cooling, breeding, and shielding mechanism. Absorbs high energy neutrons, preventing them from escaping outside the chamber and from colliding with other device components. There, the neutrons can react with enriched lithium alloys to produce tritium needed to sustain the reaction.
First Wall	Lines the reactor and protects outer vessel components from the high-temperature plasma.
Deuterium-Tritium(D-T) Fuel Target	A pellet containing the fuel that will be compressed and heated to create a fusion reaction.
Final Optics System	Final stage of the main laser system that handles beam conditioning, frequency conversion, focusing, diagnostic sampling, and debris shielding. Converts infrared light to UV light.
Vacuum Pumping	Draws gas molecules from the chamber to create a vacuum.
Control System and Diagnostics	Processes input data collected from the target chamber and regulates the behavior of other systems using control loops.
Vacuum System	Mechanism consisting of heat exchangers, coolants, filters, and pumps through which a vacuum can be created.
Tritium Recovery Plant	Manages and stores tritium fuel source.
Primary Heat Transfer System	Circulates water coolants through reactor fuel channels to remove heat and transfer them to generators.
Energy Storage System	Stores energy from a power network in a form which can be converted into another form for later use.
Exhaust	Wasted gas and heat expelled from the energy conversion processes.
Power Conversion System	Converts the energy from the fusion reaction to usable electrical energy.
Steam and Turbine Generator	Extracts thermal energy from pressurized steam to do mechanical work on a rotor. The power converter then transforms mechanical energy from the rotor to electrical energy.
Power Distribution	Delivers power produced by the fusion plant to users.

Acknowledgements

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